Is it possible to predict karstified horizons in tunneling?

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Abstract

Predicting the position of karst voids for tunnel construction is very important, since they induce economic, social, security-related and environmental problems. Here it is quantitatively show that the development of karst conduits under phreatic conditions is strongly related to a restricted number of so-called inception horizons, related to geological parameters. Thus predicting the position of potential inception horizons (that is, karst conduits) is possible. This is of great interest for engineering geological purposes.

Die Vorhersage der Lage von Karsthohlräumen ist bei Tunnelbauprojekten von großer Bedeutung, da die räumliche Ausdehnung und Orientierung von Hohlräumen zu wirtschaftlichen, gesellschaftlichen, sicherheits- und umweltrelevanten Problemen führen können. Wir konnten quantitative zeigen, dass die Entwicklung von phreatischen Karströhren an so genannten „inception horizons“ gebunden ist. Daher wäre es möglich die Position dieser bevorzugt verkarsteten Horizonte (respektive Karsthohlräume) vorherzusagen, was für ingenieurgeologische Belangen von großem Interesse ist.

1. Introduction

Many recent tunnel constructions in Switzerland (e.g. Sauges Tunnel, Engelberg Tunnel, Flims Tunnel and Alpnach Tunnel) have shown that any uncertainties in the geology of the rock-volume being tunnelled through, including those related to karst processes, is a major issue, since they may lead to economic, social, security-related and environmental problems. Despite this, the prediction of karstic dissolution voids currently lacks a scientific background. Although methods for the detection of such voids a few meters in front of tunnel working faces are being developed (e.g. Pesendorfer & Loew, 2004), no method for their prediction at a more regional-scale is available.

Research carried out by karst scientists during the last 30 years shows that the development of dissolution voids is not random (Kiraly, 1968; White, 1970; Waltham, 1971; Palmer, 1989; Klimchouk & Ford, 2000). However, most efforts have been dedicated to the understanding of the processes and, in particular, the time-scale at which dissolution voids can develop. Only a very restricted number of studies (Palmer, 1989; Lowe, 2000; Klimchouk & Ford, 2000) have attempted to analyse and understand the geometry of dissolution voids (karst conduits in most cases), to provide keys for the prediction of conduit positions, orientations and characteristics.

A rough prediction of the position of karst conduits can be made by tracing experiments. However, although the map produced by Quinlan and Ray (1981) is a well-known example of this type of prediction, it was drawn in 2D (plan view) and was very imprecise, having an accuracy of only ± 500 m. Further, it was based on hundreds of tracing experiments and thousands of borehole data, neither of which are practical during a tunnelling project.

An alternative way to address this problem is to study the hydrogeological conditions that prevailed during the karstification of a rock mass. Such studies measure the fracture characteristics (mainly their frequency and orientation) from which conduit directions were derived (Kiraly, 1968; Jamier & Siméoni, 1979; Eraso & Herrero, 1986; Blanc & Nicod, 1990). However, in many cases the authors did not consider the coupling of hydraulic conditions in the speleogenetic process and their methods were limited to descriptions of the relationship between the geological parameters (mainly fractures) and the known conduit directions. Since the influence of non-geological boundary conditions (mainly the respective positions of the recharge areas and the springs) is at least as significant as that of the geology, it was not possible to fully establish and quantify the control that fractures had in the development of the karst conduit networks. Consequently, this type of approach has a very limited capacity to predict conduit positions.

Numerical modelling has also been used to examine karstification processes. This included the atypical kinetics of calcite dissolution as well as the change of flow conditions, from laminar to turbulent, as the conduit size increased (Dreybrodt & Siemers, 2000). Such models allow hypotheses to be verified and synthetic karst systems to be generated using a range of initial and boundary conditions. However, so far, they have not often been used for conduit geometry prediction, but rather for the assessment of the time duration over which conduits develop. Hence the high uncertainties inherent in predictions of the position of karst conduits have not diminished significantly in the last 30 years.

Examination of published material revealed interesting information about the position of conduits. Rauch & White (1970), Waltham (1971) and later Palmer (1974, 1975, 1989) combined detailed observations of caves and their geological contexts to suggest that caves develop along a restricted number of bedding planes within a limestone series. Although this idea is still adopted in more recent publications (Lowe, 1992, 2000; Osborn, 1999; Klimchouk & Ford, 2000), no qualitative evidence of the existence of such inception horizons, these being the discrete planes within a rock mass that are favourable to karstification, has been documented. Nevertheless, a method which demonstrates the existence of inception horizons has been outlined in this paper. Further, by applying the technique to several case-studies, it has been possible to prove their existence and to quantify their significance. Essentially, it is now possible to quantify the probability of karst occurrences inside a karst massif by reconstructing the hydrogeological history and identifying inception horizons.

2. Methods

On the assumption that karst conduits develop along discrete preferred surfaces within a carbonate mass, then such surfaces (inception horizons) will be either bedding planes or fractures such as joints and faults. If so, then the space close to these surfaces should be more densely occupied by conduits than the remainder of the rock-mass. In other words, the spatial distribution of conduits should be neither uniform nor random, but rather should follow a systematic 3D structure. The geometry of this structure will depend on the hydraulic conditions that prevailed during the development of the karst as well as on the 3D pattern of inception horizons, which, in turn, is a function of the geology.

To analyse the complex geometry of cave systems in 3D, a software tool has been developed which provides a statistical analysis of the relationships between the conduit network geometry, the geological setting and the hydrogeological context of a large cave system. The software determines the shortest distance between a conduit segment and a reference geological surface (in most cases a 3D representation of the bottom of the limestone series) and calculates the distribution as a histogram of cave segments in relation to their distance from the reference horizon. Inception horizons, being horizons where karst development is concentrated, appear as peaks in the histogram, representing preferred distances from the reference horizon (Fig. 1).

To use the program, 3D models of both the cave system and the geology are required; the quality of the models directly influences the precision at which inception horizons can be defined. For instance, a high degree of precision is required to define whether conduits developed along a particular bedding plane in all respective compartments offset by faults. To obtain the necessary precision, geological models should be based on digital terrain models, geological maps and descriptions, air-photo interpretations and observations in the cave systems. The 3D models of the caves are computed from cavesurvey data. The software also calculates the distribution of conduits (cumulate length) with respect to the elevation. This is useful for identifying the the various evolutionary stages of the cave system (Palmer, 1987). Once statistically identified as having being highly karstified, these particular bedding planes must be verified by field observations.

3. Results

The analysis described above has been applied to a number of large cave systems from all over the world (Table 1). The systems analysed had several specific properties:

- The explored and surveyed conduit networks have a sufficient minimum length (at least 5 km).
- The systems represent various geological settings (lithology, tectonics, age, etc.). However, the analysis was limited to cave systems in limestone and/or dolomite formations.
- The caves were formed only by meteoric water, without or with only a negligible hypogenic origin (hydrothermal or acidic gas).
- Evolution of the systems took place, at least partly, under phreatic conditions. This is very important, because only conduits developed under phreatic conditions reflect the initial state of cave development.

For these examples, the observed distribution of karst conduits is neither random nor homogeneous but controlled at the regional scale by a limited number of discrete bedding planes and hydrogeological boundary conditions. This documents statistical evidence of the inception horizon hypothesis of Lowe (1992). The number of horizons in the limestone and dolostone sequences studied varied between two and seven.

In contrast to Davies (1960), who postulated that the angle of dip of bedding planes is a key factor in cave development, the present study found no evidence for such a relationship. In all cases, a strong bedding plane bounded network of phreatic karst conduits, independent of the local dip of the bedding, has been found. However, the flow may follow the dip or strike of bedding planes, depending on the prevailing hydrogeological boundary conditions (i.e. recharge/discharge zones).

Further, the data indicates that joints and faults are responsible for the local position and orientation of the conduits within (or along) inception horizons. That is, statistically, most conduits lie at the intersections of joints and bedding planes (Fig. 2).

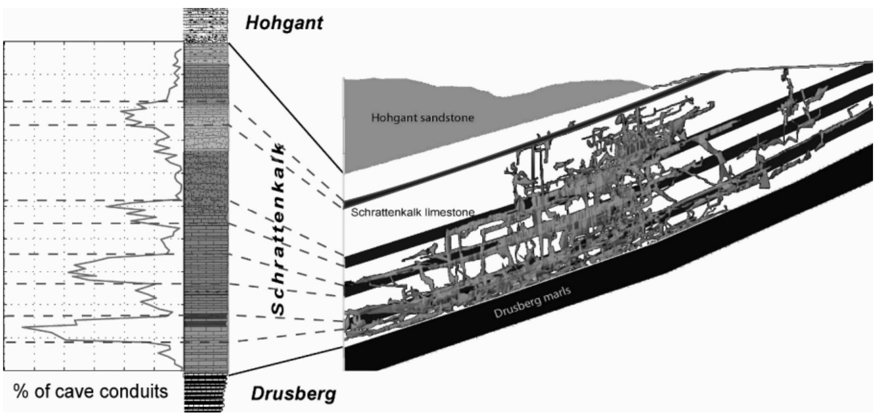

Figure 1 : Projection of one part of the Siebenhengste cave system. Four potential inception horizons can be identified within the Schrattenkalk limestone, which is nearly 180 m thick.

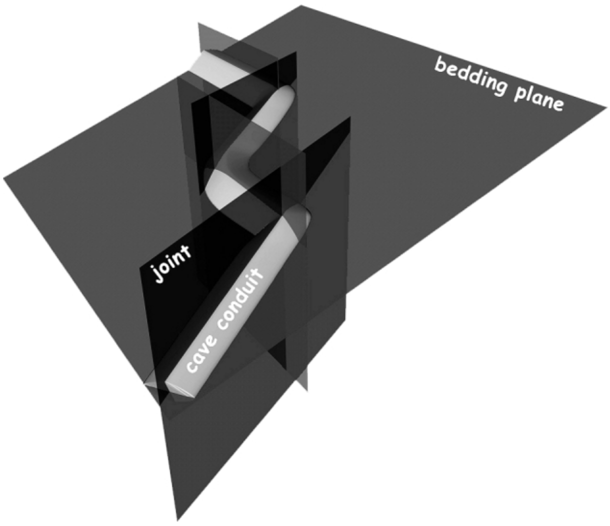

Figure 2: Schematic representation of the role of joint sets and bedding plane for the position and orientation of cave conduits.

In most cases, inception horizons correspond to bedding planes and often the former can be easily recognised in caves. For example, anastomoses (a network of branching, intersecting, and rejoining channels in a two dimensional system; Slabe, 1995) are frequently developed along such preferential planes (Fig. 3). Anastomoses, which are generally formed through dissolution by slow, poorly directed phreatic flows along a discontinuity, represent an important element in the early stages of cave development and are best described as protoconduits. Most protoconduits are abandoned during the later stages of conduit development, when one conduit offers better flow conditions, such that it increases in size at the expense of the others. Anastomoses are evidence of preferential karstification along a given bedding plane; that is, of an inception horizon.

From our field observations as well as from published data (Lowe, 2000) several reasons can be postulated for a bedding plane becoming a potential inception horizon. These reasons apply only partially to fault planes.

- Increased initial permeability. In bulk carbonate sequences, bedding planes may provide the first possible water routes because of a slightly higher primary permeability than the adjacent rock mass.
- Aquicludes. Some bedding planes (e.g. shaly ones) are more impervious (lower permeability) than the surrounding rock mass. They act as aquicludes, and force water to flow at the contact zone with the adjacent carbonate (flow concentration).
- Turning non-aggressive water into corrosive solutions. The weathering of certain minerals, such as sulphides, can produce acidic solutions, which can at least locally increase the dissolution capacity. Such an additional acidic dissolution has a minimal effect in the context of the later stages of passage formation, but its contribution to the initial permeability development of a bedding plane can be significant.
- An increase of the primary porosity of the bedding planes is also possible, through the dissolution of highly soluble minerals such as gypsum, or related to a change in mineralogy as for example dolomitization or dedolomitization, or slight changes in the calcite chemistry (such as high/low magnesium calcite) which strongly affects the mineral stability, or by tectonic slip along the bedding plane.

Note that only a small proportion of the bedding planes present in a carbonate sequence seems to be favourable to karstification; most bedding planes play no significant role in karst development.

4. Case study: the Nidlenloch, Switzerland

The approach used for the examples described in Table 1 is illustrated here in detail with a case-study of Nidlenloch (Switzerland).

4.1 Regional context

The Nidlenloch (length 7,000 m, difference in elevation 420 m; explored by the Arbeitsgemeinschaft Nidlenlochforschung) formed in well bedded oolitic sparitic limestones (Malm) on the northern flank of the Weissenstein anticline, north of Solothurn, in Switzerland. The bedding orientation is essentially constant (092/50° N) and no major faults offset the limestone beds (Fig. 5).

Cave passages follow either the dip of the bedding planes toward the north, or the east-west strike of the beds. A horizontal network of partially labyrinthine passages has been recorded in the central part of the cave. Other parts of the cave also have typical phreatic passage networks. Currently, the cave is traversed by very local or temporary streamlets, which barely contribute to the current karst drainage. Nevertheless, three different palaeophreatic stages have been distinguished (Fig. 4). The first stage, located at ca. 1,200 metres above sea level (a.s.l.), flowed mainly in an W-E direction. The second stage, at ca. 1,100 metres

Figure 3: Anastomosis in the Nidlenloch cave system. (Photo: Mirjam Widmer)

a.s.l. had the same main direction whilst the third phreatic stage, at ca. 950 metres a.s.l, had a predominantly SE-NW flow direction. This change of flow direction was caused by the evolution of the valleys at the surface and, related to this, changes in the hydrogeological boundary conditions. It has been noted that the phreatic conduits of each stage makes loops in the order of some tens of metres of elevation.

Conduits of modest dimensions are often interrupted by breakdown, or low points filled with clay, which reflect the advanced age of the cave. Despite the significant depth of the cave, pits are rare and their depth does not exceed 20 metres. No larger chambers and only rare flowstone speleothems have been found.

4.2 Statistical evidence of the existence of inception horizons

A histogram of the distance of the karst conduits to a geological reference horizon clearly shows some obvious peaks (Fig. 6), indicating that the cave passages are not distributed randomly within the limestone mass, but lie at discrete horizons more favourable to karstification. The peaks indicate that Nidlenloch essentially developed at four stratigraphic horizons; these account for ca. 80% of the surveyed cave conduits.

A stereographic projection of conduit orientations shows that the majority are located in the northern hemisphere and more-or-less lie on the great circle representing the bedding-plane orientation. Two other preferred directions (E-W, N-S), which correspond to two sets of joints, have been identified and can also be seen on a plan view of the cave (Fig. 4).

This analysis indicates that the cave developed mainly at four stratigraphic horizons, along which the conduits followed the intersection of the bedding plane with two predominant joint sets. The direction of conduit development was determined by the hydrogeological context. This was confirmed by a computer generated 3D visualisation of the cave network.

Name of the cave System	Country	Length [m]	Depth [m]	Litology	Number of inception horizons
Mammoth Cave System	Kentucky, United States	579.400	115	Limestone	5
Hölloch & Silbernsystem	Schwyz, Switzerland	192'000 & 37'700	940 890	Limestone	3-4
Siegenhengste-Hohgant Höhlensystem	Bern, Switzerland	171.000	1340	Limestone	5-7
Shuanghedongqun	Suiyang, China	102.000	370	Dolomite and dolomitic limestone	2
Hirlatzhöhle Dachstein	Oberösterreich, Austria	92.940	1010	Limestone	6-7
Ogof Draenen	South Wales, United Kingdom	66.100	100	Limestone	3
Dachstein-Mammuthöhle	Oberösterreich, Austria	65.800	1200	Limestone	4-5
Schwarzmooskogel-Höhlensystem	Oberösterreich, Austria	56.400	1030	Limestone	6-7
Schrattenhöhle & Bettenhöhle	Obwalden, Switzerland	19.650	575	Limestone	2
Réseau des Grottes aux Fées & Grotte de l'Orbe	Vaud, Switzerland	7000 & 6000	135 115	Limestone	3
Hölloch im Mahdtal	Allgäu, Germany	9.300	460	Limestone	3
Wägital Lachenstock, K10, Plattenloch	Schwyz, Switzerland	9.000	270	Limestone	5
Nidlenloch	Solothurn, Switzerland	7.000	420	Limestone	4
Réseau de Covatannaz	Vaud, Switzerland	4.450	105	Limestone	2

Table 1 : List of analysed cave systems with the number of statistically identified inception horizons.

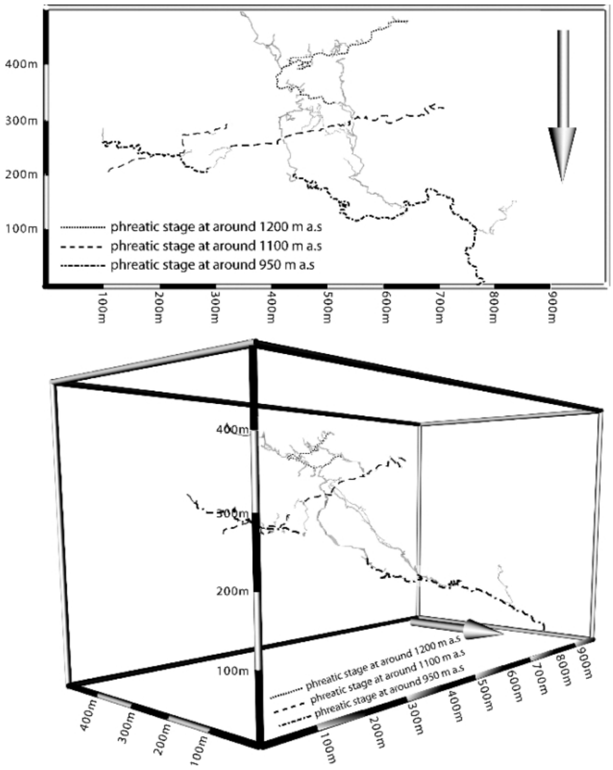

Figure 4: Plan and 3D views of the Nidlenloch: the three different palaeophreatic stages are shown in dashed lines (arrow shows to north).

4.3 Field verification of the inception horizons

Field investigations in the cave confirmed the existence of inception horizons at the positions derived from the cave geometry analysis (Fig. 6). Although the favourable horizons appear in the histograms as peaks of five to 15 metres thickness, in the field they occur along single bedding planes, with a thickness in the order of centimetres to decimetres. This difference is caused by uncertainties in the position of the geological reference surface (± 5 m), in the cave survey (± 5 m) and in the position of the bedding plane within the cave conduit profile (up to ± 2 m).

Detailed observations of the horizons indicated some possible reasons why those specific bedding planes were favourable to karstification. At two horizons, shearing has occurred along the bedding plane after conduit development; probably some shearing also occurred before or during conduit formation. Remarkably, flowers and needles of gypsum have been observed along or nearby the inception horizons. This implies the production of H_2S or possibly H_2SO_4, since the gypsum was probably derived from pyrite. At this stage, however, it is not possible to asses the role of these parameters or even to be sure that they played a significant role in preferential karst development along these horizons.

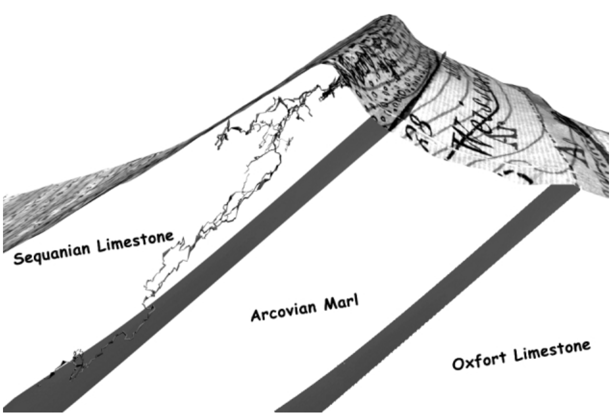

Figure 5: Simplified geology of the Nidlenloch area, with a 3D view of the cave (line of sight towards the NE).

The case-study results have been compared with observations in the nearby Weissenstein railway tunnel, constructed in 1908, which is 3.7 kilometres long and crosses the Wissenstein anticline at around 700 metres a.s.l.. Although the tunnel walls are now concrete-lined, documentation of the tunnel construction (Buxtorf, 1908) indicates that the tunnel crossed karst conduits three times. These were filled with sediments, with only a minor water-flow and once a larger spring, with a discharge of around 80 l/s, was encountered. The stratigraphic positions of these occurrences correspond quite well with the favourable karst horizons determined from analysis of the Nidlenloch cave system geometry.

5 Discussion and Conclusions

An analysis of 14 of the largest cave systems in the world demonstrates that the development of karst conduits under phreatic conditions is strongly related to inception horizons. This is the first clear indication that it is possible to quantify the degree of conduit concentration along such inhomogeneities.

The position of inception horizons can be predicted by documenting the specific properties of bedding planes, as well as of valley and cave evolution. Up to now, a rough idea of the relevant properties of inception horizons has been determined; both tectonic slip along bedding planes and the presence of pyrite are probably significant factors in their development.

Although data from other sites seems to confirm this hypothesis, it is not yet clear if these factors would also apply in other limestone series and other karstification conditions. Consequently, the prediction of karst occurrences remains very challenging.

Compared to the usual 2D analyses of cave systems (e.g. vertical distribution of conduits in order to identify cave levels or plan views to work out the relationship between cave development and fractures) our 3D analysis allowed us to couple the geological and hydrogeological contexts. This has shown that caves evolved along a restricted number of discrete stratigraphic horizons, at which the conduits followed the intersection of the bedding plane with the predominating joint sets. Nevertheless, the main direction of the conduits was determined by the hydrogeological context. On-going studies will likely provide a clear improvement in the prediction of voids in karst massifs, which is especially important for tunnelling or dam construction.

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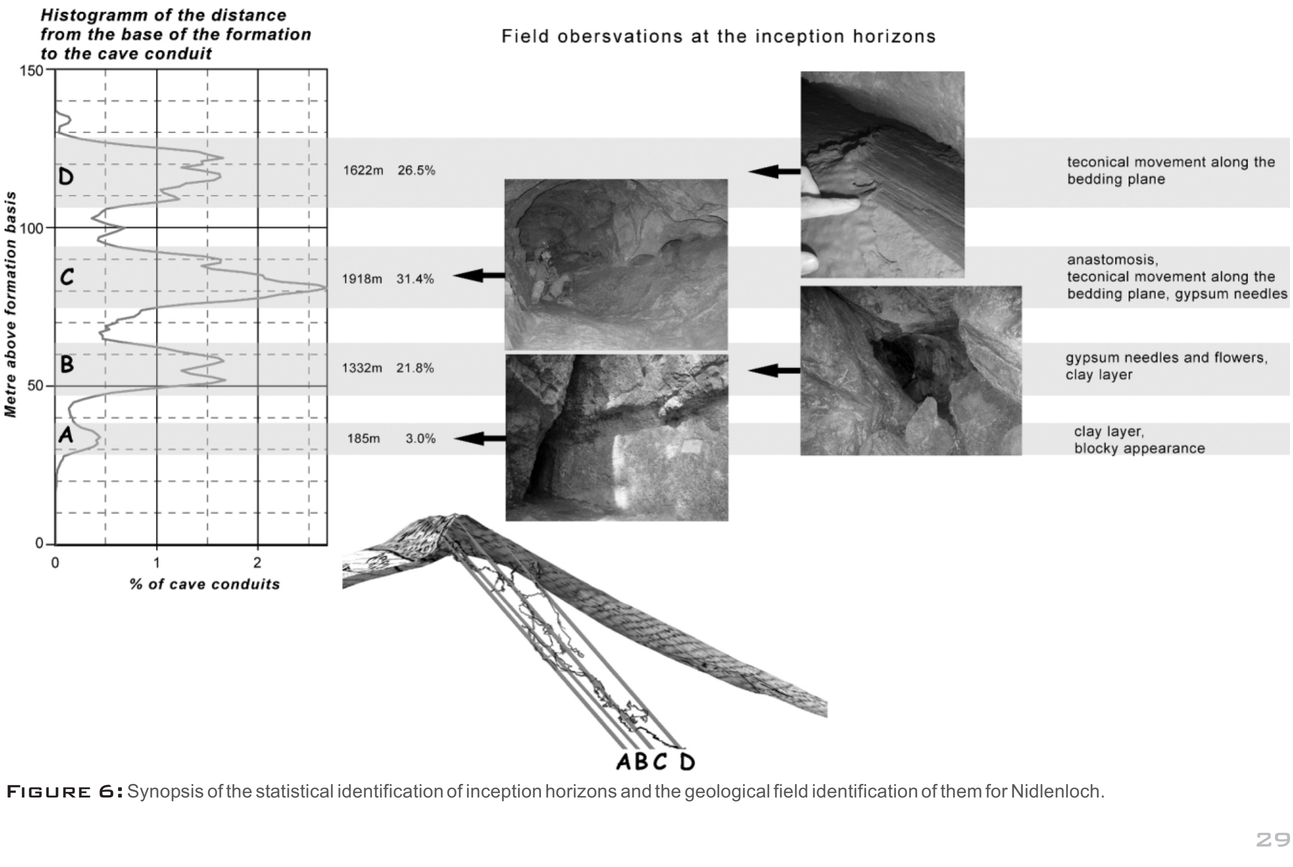

Figure 6: Synopsis of the statistical identification of inception horizons and the geological field identification of them for Nidlenloch.

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